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Improving Quality through Instrumental Color Measurement

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EXECUTIVE SUMMARY

The traditional method for determining the acceptability of fabrics relative to a given standard color is visual shade evaluation. However, visual color assessment is subjective and time-consuming. In contrast, instrumental color measurement, used in conjunction with established standards for quantifying color differences, provides an objective and consistent methodology for judging acceptability of colored goods.

The US Army Natick Research, Development, and Engineering Center (Natick) and the Defense Personnel Support Center (DPSC) have developed procedures for instrumental color evaluation. The usefulness of these procedures has been hampered by lack of conformance to industry standards, requiring that contractors be supplied color measurement equipment, and proprietary color evaluation procedures.

A careful analysis of the development of the proprietary government procedure (the ΔA color difference formula) reveals that it is based on the same color physics and mathematics as an industry standard procedure (the ΔE_{CMC} color difference formula). The significant difference in these approaches is that the industry standard is widely available in commercial instrumentation and software and its applicability to all shades. Neither can be said for the proprietary government procedure.

In the few cases where color acceptability standards have been established using the proprietary government procedure, these standards can be converted to industry practice with remarkable consistency. Although more extensive trials are recommended, there appear to be no technical difficulties in replacing the proprietary government procedures with industry standard procedures for color acceptance.

INTRODUCTION

The traditional method for determining the acceptability of fabrics relative to a given standard color is visual shade evaluation. However, visual color assessment is subjective and time-consuming. Its expense and inconsistency do not promote quality in manufacturing. In contrast, instrumental color measurement, used in conjunction with established standards for quantifying color differences, provides an objective and consistent methodology for judging acceptability of colored goods.

The US Army Natick Research, Development, and Engineering Center (Natick) and the Defense Personnel Support Center (DPSC) currently use instrumental color evaluation to determine the acceptability of fabrics relative to a given standard. The procedures that were developed and are now used by Natick and DPSC incorporate a proprietary color difference formula known as ΔA [2]. The usefulness of these procedures has been hampered by non conformance to industry standards, requirements that contractors be supplied color measurement equipment, and proprietary color evaluation procedures.

The objective of this project was to build on the work begun by Natick and DPSC in instrumental color measurement by converting these proprietary methods to ones based on industry standards. Color tolerances for acceptability are developed using widely available and industry accepted procedures for measuring color difference. Such tolerances can be used with commercially available color measurement instruments, eliminating the need for government supplied equipment. Reliance on industry standard procedures can be expected to significantly reduce the current time required for color acceptability assessment and improve quality through consistent, objective, and reproducible test methods.

The Colour Measurement Committee of the Society of Dyers and Colourists has refined an existing color difference formula to develop the ΔE_{CMC} formula [1, 3] which has become an industry standard for quantifying color differences. Our first task is to compare the mathematics of the ΔA color difference formula with the calculations associated with ΔE_{CMC} and to determine how these methods compare on a set of representative colors. Next, we will focus on demonstrating the feasibility of using the ΔE_{CMC} color difference formula to set acceptability tolerances for two specific fabrics, four-color woodland camouflage and three-color desert camouflage. Finally, recommendations will be made based on the results of the analyses performed.

ΔA VS. ΔE_{CMC} COLOR DIFFERENCE FORMULAE

Color Acceptability Ellipsoids

There are several methods for measuring the color difference between a sample and a standard or between two samples. Two particular methods, ΔA and ΔE_{CMC} (denoted simply ΔE hereafter) are examined here.

Both ΔA and ΔE are based on color acceptability ellipsoids in CIELCH color space. Given a standard color and a sample color, the sample is *acceptably* close to the standard if it lies on or within an ellipse centered at the standard. The ellipse is oriented along the lightness, chroma, and hue axes of the standard (Figure 1). The lengths of the semi-axes of the ellipse are the lightness, chroma, and metric hue tolerances associated with the standard. The value of ΔA or ΔE for a sample point is just the Euclidean distance from the standard to the sample where the differences in lightness, chroma, and metric hue between the sample and the standard have been scaled by their respective tolerances.

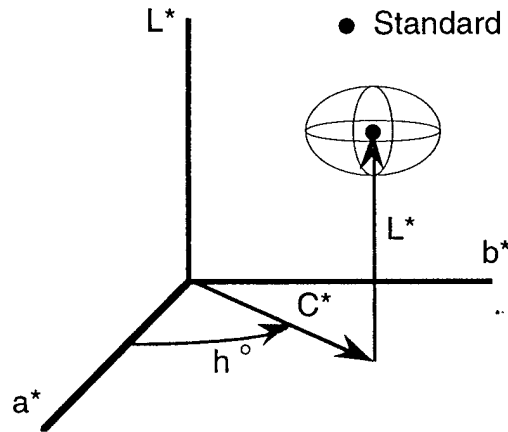


Figure 1. Acceptability ellipsoid in CIELab/CIELCH color space

Specifically, the color difference between sample and standard is shown in equations (1) and (2) for ΔA and ΔE respectively.

$$\Delta A = \left[\left(\frac{\Delta L}{v_0} \right)^2 + \left(\frac{\Delta a \cos \theta + \Delta b \sin \theta}{c_0} \right)^2 + \left(\frac{\Delta b \cos \theta - \Delta a \sin \theta}{h_0} \right)^2 \right]^{1/2} \quad (1)$$

$$\Delta E = \left[\left(\frac{\Delta L}{T_L} \right)^2 + \left(\frac{\Delta C}{T_C} \right)^2 + \left(\frac{\Delta H}{T_H} \right)^2 \right]^{1/2} \quad (2)$$

where

(L₀, a₀, b₀) is the given standard in L*, a*, b* coordinates;

(L_0, C_0, h°) is the standard in L^*, C^*, h° coordinates

(as usual, C and h° are defined as $C = \sqrt{a^2 + b^2}$ and $h^\circ = \tan^{-1}(b, a)$);

$\Delta L = L^* - L_0$ is the difference in lightness between the two samples;

$\Delta a = a^* - a_0$ is the difference in a^* between sample and standard;

$\Delta b = b^* - b_0$ is the difference in b^* between sample and standard;

$\theta = \tan^{-1}(b_0, a_0)$ is the hue angle of the standard;

$\Delta C = C^* - C_0$ is the difference in chroma between sample and standard;

$\Delta H = \sqrt{\Delta a^2 + \Delta b^2 - \Delta C^2}$ is the metric hue difference between sample and standard;

(v_0, c_0, h_0) are the lightness, chroma, and hue tolerances for ΔA ; and

(T_L, T_C, T_H) are the lightness, chroma, and hue tolerances for ΔE (semi-axis lengths).

The scaled distance from the standard to the surface of the ellipse is called the *critical value* or *acceptability tolerance* for that standard. Some effort is ordinarily made to set the tolerances so that the critical value is near one. However, depending upon the particular end use of the color product, the critical value for ΔA or ΔE may be greater or less than one. We denote the acceptability ellipsoids associated with ΔA and ΔE (both with a critical value of one) by A_{ellipse} and E_{ellipse} respectively.

Some comment about the interpretation of the color acceptability ellipsoid is in order here. It should be clear that the boundary of the ellipsoid cannot provide an absolutely sharp demarcation between those colors that are acceptable and those which are not. Two samples, one just barely within the ellipsoid, the other just without, can be made arbitrarily close in color but the inner sample is labeled acceptable and the outer, unacceptable. Actually, the boundary of the ellipsoid represents that part of color space where the acceptability criteria become ambivalent. For visual assessment, the more "expert" the observer, the "sharper" the acceptability region becomes. This interpretation of numerical color acceptability is often overlooked or ignored, but is an important and real aspect of color acceptability.

Ellipsoid A_{ellipse}

The equation for A_{ellipse} in terms of the CIELab system is given as

$$1 = \left(\frac{\Delta L}{v_0} \right)^2 + \left(\frac{\Delta a \cos \theta + \Delta b \sin \theta}{c_0} \right)^2 + \left(\frac{\Delta b \cos \theta - \Delta a \sin \theta}{h_0} \right)^2, \quad (3)$$

where all terms are defined as above except the Δ values are taken relative to the standard. The trigonometric terms in (1) and (3) suggest a change in coordinate axes through a simple rotation. In particular, a counterclockwise rotation through the hue angle of the standard (θ) is appropriate. Writing the difference between the sample and standard chroma as ΔC_A and the difference in metric hue as ΔH_A , the differences in chroma and hue used in the ΔA formula can be written

$$\begin{pmatrix} \Delta C_A \\ \Delta H_A \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \cdot \begin{pmatrix} \Delta a \\ \Delta b \end{pmatrix}. \quad (4)$$

That is, $\Delta C_A = \Delta a \cos \theta + \Delta b \sin \theta$, $\Delta H_A = \Delta b \cos \theta - \Delta a \sin \theta$, and (3) is seen to be essentially the same as (5) below except for the calculation of the Δ values.

It is evident from equations (3) and (4) that A_{ellipse} is centered at (L_0, a_0, b_0) ; the ellipse is oriented with the lightness, chroma, and metric hue axes; and the lengths of the lightness, chroma, and hue semi-axes are (v_0, c_0, h_0) respectively. ΔC_A and ΔH_A are used to denote the difference in chroma and metric hue for ΔA since these definitions differ slightly from the standard definitions given below.

Ellipsoid E_{ellipse}

The equation for E_{ellipse} in terms of the CIELCH system is given as

$$1 = \left(\frac{\Delta L}{T_L} \right)^2 + \left(\frac{\Delta C}{T_C} \right)^2 + \left(\frac{\Delta H}{T_H} \right)^2. \quad (5)$$

From equation (5) note that E_{ellipse} is centered at the standard (L_0, a_0, b_0) — (L_0, C_0, h^0) in lightness, chroma, hue coordinates; the lengths of the lightness, chroma, and hue semi-axes are T_L , T_C , and T_H , respectively; and the hue axis of the ellipsoid is at an angle of h^0 degrees with the a^* axis (the hue angle of the standard).

Comparison of A_{ellipse} and E_{ellipse}

The ellipsoids A_{ellipse} and E_{ellipse} have the same center and are oriented in exactly the same manner in the CIELab/CIELCH space; i.e., the chroma axes of A_{ellipse} and E_{ellipse} are at the same angle $\theta = h^0$ with respect to the a^* axis. There are two differences between these ellipsoids. The first is in the lengths of their semi-axes, corresponding to lightness, chroma, and hue tolerances. The tolerances v_0 , c_0 , and h_0 for A_{ellipse} are determined by historical data, whereas T_L , T_C , and T_H for E_{ellipse} are specified by the CMC color difference formula. (Note that the CMC color tolerances are based on extensive historical and experimental data [3].)

The second difference lies in the definitions of differences in chroma and metric hue, ΔC and ΔH . ΔE , ΔC , and ΔH are specified as above while ΔC_A and ΔH_A are associated with a rotation in coordinate axes. While it is always true that $\Delta C_A^2 + \Delta H_A^2 = \Delta C^2 + \Delta H^2$, the delta values calculated by the two methods are not always the same.

Mathematical Differences between ΔA and ΔE_{CMC}

There are two portions of the calculations for ΔA and ΔE that can produce differences in the color distance between a sample and a standard. As noted above, although the respective color difference formulae are essentially identical, there is a slight difference in the calculation of ΔC

and ΔH . This is examined in the next section. In addition, the tolerances used in ΔA and ΔE are not identical. These are compared in conjunction with the critical values for those colors used in the original development of ΔA in the following section.

Chroma and Hue Difference Formulae

It is evident from equation (3) that ΔC_A and ΔH_A are determined by the rotation of the axes (a^* , b^*) to the (C^* , H^*) system as illustrated in Figure 2. (Recall $\Delta C_A = \Delta a \cos \theta + \Delta b \sin \theta$ and $\Delta H_A = \Delta b \cos \theta - \Delta a \sin \theta$.) The difference in chroma, ΔC , is computed directly by $\Delta C = C^* - C_0$, where C^* and C_0 are the chroma values of the sample and standard, respectively. The difference in metric hue, ΔH , depends on ΔC — $\Delta H = \sqrt{\Delta a^2 + \Delta b^2 - \Delta C^2}$. For samples close to the standard, the chroma and hue differences for the two methods are practically the same. For samples further away from the standard, the differences are more pronounced. These observations are illustrated in Figure 3 which graphically show the difference between ΔC and ΔC_A . Although the corresponding difference in metric hue is not graphically depicted, since $\Delta C_A^2 + \Delta H_A^2 = \Delta C^2 + \Delta H^2$, the extent of the chroma difference must be reflected in the hue difference. A numerical comparison of the difference arising from these two methods of calculation is given in the next section.

Numerical Comparison of Chroma and Hue Difference

The preceding figures show how differences in the calculation of ΔC and ΔH can arise in using the ΔA and ΔE color difference formulae. As noted, these differences are likely to be significant only if the difference in hue angle between the standard and sample is large. To indicate the practical significance of these differences, the colors and limit samples used in the initial development of ΔA are examined. (In the following tables, a limit sample denoted FY means "full yellow," TB means "thin blue," etc.)

For reference, the colorimetric values of the limit samples and three ellipsoid boundary points for the four sets of colors studied in [2] are given in Table I. For these sample points, the chroma and hue differences between the samples and standard are calculated according to the ΔE and ΔA equations (Table II). A cursory examination of these values shows that they are quite similar. A better comparison can be made by calculating the change in ΔE color distance that would result from using ΔC_A and ΔH_A rather than ΔC and ΔH in the ΔE formula.

The color difference between standard and sample and the percentage difference resulting from the use of ΔC_A and ΔH_A are shown in the last two columns of Table II. For each color the average change in ΔE is less than one percent. At least for these samples, it makes little difference in the value of ΔE whether the chroma and hue differences are calculated using the methods of ΔA or ΔE . As expected, for practical situations where the samples are relatively close to the standard, there is no significant error made in using the ΔA method for calculating ΔC and ΔH .

At the same time, there is little reason to prefer this method of calculation over that employed in ΔE , which will be used for the remainder of this report. (CMC (2:1), the industry standard for acceptability, was used in the ΔE calculations. Table II also shows the delta values associated with the acceptability ellipsoid E_{ellipse} .)

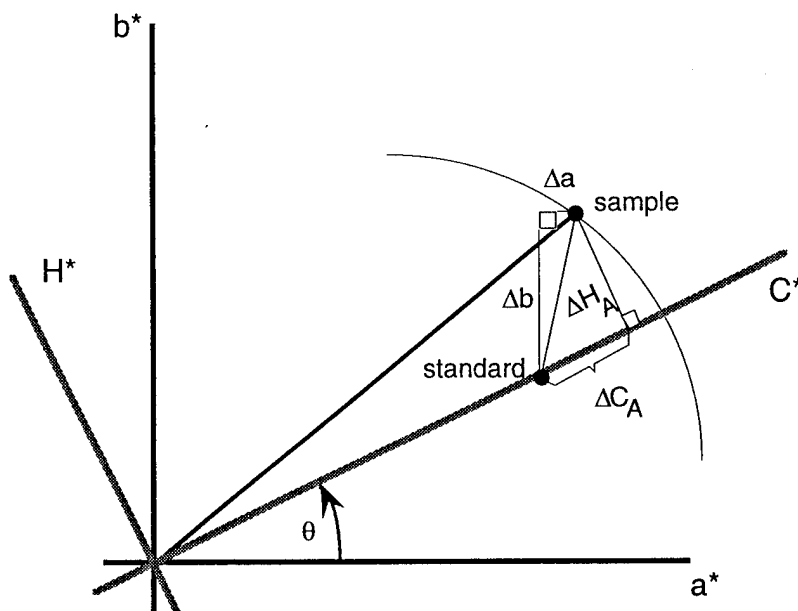


Figure 2. Chroma and hue differences as calculated using ΔA

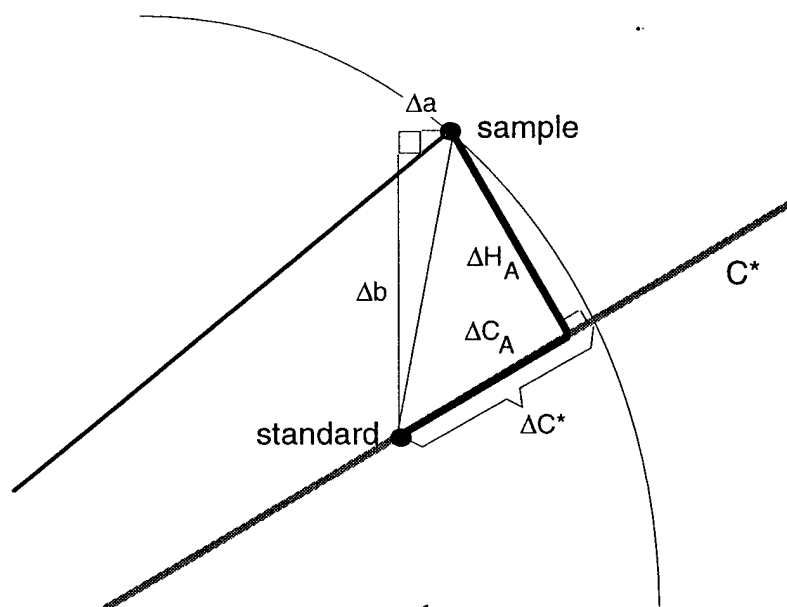


Figure 3. Chroma and hue differences for ΔA and ΔE

Table I. Names and Colorimetric Values for ΔA Colors

SAMPLE	L*	a*	b*	C*	h°
Olive Green Standard	31.71	-3.76	9.31	10.04	111.99
FY	32.29	-5.29	9.76	11.10	118.46
FS	31.72	-4.92	9.45	10.65	117.50
FG	31.87	-3.85	8.03	8.91	115.62
FB	32.35	-4.28	8.51	9.53	116.70
FR	32.10	-4.65	9.57	10.64	115.91
TG	32.23	-3.74	8.07	8.89	114.87
TY	32.43	-4.26	8.78	9.76	115.88
TB	33.79	-4.87	8.80	10.06	118.96
TS	32.65	-4.89	9.75	10.91	116.64
E L*max	33.39	-3.76	9.31	10.04	111.99
E C*max	31.71	-4.18	10.36	11.17	111.99
E H*max	31.71	-4.32	9.09	10.06	115.41
Tan Set No. 1 Standard	57.48	2.05	15.64	15.77	82.53
FY	57.26	2.92	16.91	17.16	80.20
FS	56.47	3.31	16.38	16.71	78.58
FG	57.54	2.49	16.36	16.55	81.35
FB	58.00	2.35	15.27	15.45	81.25
FR	58.52	3.41	15.91	16.27	77.90
TR	58.42	2.67	16.30	16.52	80.70
TY	58.50	2.53	16.74	16.93	81.41
TB	57.94	2.14	15.27	15.42	82.02
TS	58.96	2.21	15.34	15.50	81.80
E L*max	58.99	2.05	15.64	15.77	82.53
E C*max	57.48	2.18	16.66	16.80	82.53
E H*max	57.48	1.61	15.70	15.78	84.13
Tan Set No. 2 Standard	56.43	2.47	15.09	15.29	80.70
FY	55.66	2.24	15.60	15.76	81.83
FS	56.06	2.80	15.07	15.33	79.47
FG	55.97	1.82	15.12	15.23	83.14
FB	56.84	2.82	14.50	14.77	78.99
FR	56.89	3.21	15.23	15.56	78.10
TR	57.67	2.88	15.72	15.98	79.62
TY	56.92	1.86	15.60	15.71	83.20
TB	57.23	2.57	14.71	14.93	80.09
TS	57.83	2.56	14.63	14.85	80.07
TG	56.34	1.93	15.21	15.33	82.77
E L*max	57.94	2.47	15.09	15.29	80.70
E C*max	56.43	2.64	16.11	16.32	80.70
E H*max	56.43	2.04	15.16	15.30	82.35
Dark Blue Standard	22.98	0.21	-11.12	11.12	271.06
FG 1	20.93	0.16	-10.81	10.81	270.85
FS	22.59	0.04	-10.96	10.96	270.21
FG 2	22.18	-0.06	-10.79	10.79	269.68
FB	22.70	-0.25	-11.25	11.25	268.73
FR	22.34	-0.16	-10.92	10.92	269.16
TR	22.85	0.13	-11.12	11.12	270.67
TB	23.56	-0.03	-11.16	11.16	269.85
TS	22.53	0.23	-10.89	10.89	271.21
TG	23.09	0.05	-11.48	11.48	270.25
E L*max	24.01	0.21	-11.12	11.12	271.06
E C*max	22.98	0.22	-12.04	12.04	271.06
E H*max	22.98	0.86	-11.11	11.14	274.45

Table II. ΔC and ΔH and Change in Color Difference using ΔA versus ΔE

SAMPLE	ΔC	ΔC_A	ΔH	ΔH_A	ΔE	% Change
Olive Green Standard						
FY	1.061	0.990	1.191	1.250	1.668	1.7
FS	0.613	0.564	0.994	1.023	1.254	1.2
FG	-1.135	-1.153	0.598	0.563	1.172	1.0
FB	-0.515	-0.547	0.803	0.782	1.090	0.9
FR	0.599	0.574	0.707	0.728	0.984	1.0
TG	-1.146	-1.157	0.474	0.446	1.141	0.6
TY	-0.282	-0.304	0.672	0.662	0.917	0.5
TB	0.017	-0.057	1.221	1.220	1.882	0.0
TS	0.867	0.831	0.848	0.883	1.339	1.1
E L*max	0.000	0.000	0.000	0.000	1.008	0.0
E C*max	1.130	1.130	0.000	0.000	0.938	0.0
E H*max	0.018	0.000	0.600	0.600	0.691	0.0
Tan Set No. 1 Standard						
FY	1.386	1.372	-0.669	-0.698	1.255	1.3
FS	0.937	0.897	-1.121	-1.153	1.580	1.5
FG	0.775	0.771	-0.335	-0.343	0.669	0.6
FB	-0.324	-0.328	-0.349	-0.346	0.532	0.5
FR	0.498	0.444	-1.294	-1.313	1.689	0.9
TR	0.743	0.735	-0.517	-0.529	0.907	0.8
TY	1.156	1.153	-0.321	-0.333	0.982	0.4
TB	-0.355	-0.355	-0.139	-0.137	0.355	0.2
TS	-0.275	-0.277	-0.199	-0.198	0.704	0.1
E L*max	0.000	0.000	0.000	0.000	0.646	0.0
E C*max	1.030	1.030	0.000	0.000	0.700	0.0
E H*max	0.006	0.000	0.440	0.440	0.542	0.0
Tan Set No. 2 Standard						
FY	0.469	0.466	0.305	0.309	0.605	0.4
FS	0.037	0.034	-0.329	-0.329	0.448	0.1
FG	-0.062	-0.075	0.648	0.646	0.849	0.1
FB	-0.519	-0.526	-0.448	-0.441	0.697	0.8
FR	0.274	0.258	-0.702	-0.708	0.934	0.6
TR	0.691	0.688	-0.296	-0.303	0.810	0.3
TY	0.420	0.405	0.675	0.684	0.932	0.8
TB	-0.358	-0.359	-0.162	-0.160	0.472	0.2
TS	-0.439	-0.439	-0.166	-0.163	0.708	0.1
TG	0.041	0.031	0.552	0.552	0.704	0.1
E L*max	0.000	0.000	0.000	0.000	0.652	0.0
E C*max	1.030	1.030	0.000	0.000	0.710	0.0
E H*max	0.006	0.000	0.440	0.440	0.560	0.0
Dark Blue Standard						
FG 1	-0.311	-0.311	-0.040	-0.039	1.551	0.0
FS	-0.162	-0.163	-0.163	-0.162	0.381	0.1
FG 2	-0.332	-0.335	-0.263	-0.259	0.735	0.2
FB	0.131	0.122	-0.455	-0.457	0.628	0.3
FR	-0.201	-0.207	-0.365	-0.361	0.687	0.3
TR	-0.001	-0.001	-0.075	-0.075	0.137	0.0
TB	0.038	0.036	-0.235	-0.236	0.528	0.0
TS	-0.229	-0.230	0.030	0.029	0.384	0.0
TG	0.358	0.357	-0.159	-0.162	0.360	0.3
E L*max	0.000	0.000	0.000	0.000	0.769	0.0
E C*max	0.920	0.920	0.000	0.000	0.732	0.0
E H*max	0.020	0.000	0.660	0.660	0.845	0.0

Numerical Comparison of Tolerances

The acceptability of a sample for both ΔA and ΔE is determined by whether the sample lies on the surface or within the color ellipsoid centered on the standard in CIELCH color space. The size and shape of the ellipsoid in both instances are determined by the length of the semi-axes; that is, the tolerances associated with the standard. These tolerances are usually chosen so that a color difference of 1.0 is equally likely to be considered acceptable or unacceptable for that standard by an "expert" viewer. However, for particular applications, it is often desirable to establish a critical value either lower or higher than 1.0 to reflect actual practice. (The more general definition for ΔE includes a commercial factor, *cf*, for exactly this purpose.) Hence, the relative values of the tolerances are more important than their absolute values. To complete the comparison of ΔA and ΔE , we focus on the tolerance values for ΔA versus ΔE .

The role of the relative tolerances in setting color acceptability makes it difficult to make a direct comparison between ΔA and ΔE critical values. However, we can use the physical limit samples associated with the color sets discussed above to make the comparison. The ΔA critical value for each color set was calculated as the average ΔA value for the associated limit samples. Likewise, the ΔE critical value can be set to the average ΔE value for the limit samples of each standard. Table III gives a listing of the lightness, chroma and hue tolerances for the ΔA method (*v*, *c*, and *h*, respectively), the tolerances for the ΔE method (T_L , T_C , and T_H), and the ΔA and ΔE critical values for each of the four color sets.

Table III. Comparison of E_{ellipse} to A_{ellipse} for Four Color Sets						
	Tolerances (L, C, H)		Critical Values		Relative Volumes	
	ΔA	ΔE	ΔA	ΔE	Unscaled	Scaled
Olive Green	1.68 1.13 0.60	1.67 1.20 0.87	1.60	1.27	1.53	0.76
Tan, Set No. 1	1.51 1.03 0.44	2.34 1.47 0.81	1.63	0.96	4.07	0.83
Tan, Set No. 2	1.51 1.03 0.44	2.32 1.45 0.78	1.21	0.72	3.83	0.80
Dark Blue	1.03 0.92 0.66	1.34 1.26 0.78	0.80	0.60	2.11	1.34

Note that few of these critical values are close to 1.0 as might be expected from the development underlying both ΔA and ΔE . Hence, we make our comparison based on both *unscaled* and *scaled* color differences. The unscaled values are given directly by the ΔA and ΔE color differ-

ence formulae. The scaled values are obtained by scaling the tolerances for each color difference formula and color set so that the average color difference for each set of limit samples is the typical 1.0 value. The intent of this scaling is to make the ΔA and ΔE tolerances commensurate.

One way of comparing the ΔA and ΔE tolerances is to calculate the unscaled and scaled relative volumes of the color acceptability ellipsoids E_{ellipse} to A_{ellipse} . These are also given in Table III. (A value greater than 1 means that the ΔE ellipse includes more of color space than the ΔA ellipse, although not necessarily the same space. Similarly, a value less than 1 means the ΔA ellipse includes more space.) Note that the unscaled relative volumes are quite disparate, but that the scaled values are more uniform. This suggests that different acceptability criteria may have been applied in the determination of the ΔA tolerances for the different color sets. The ΔE tolerances were chosen so that a color difference of 1.0 would be viewed similarly regardless of the standard color.

A more direct comparison of the color tolerances is given in Figures 4 through 7. These figures show the relative sizes of the acceptability ellipse for chroma and hue with a side bar comparing the tolerance for lightness. Each figure includes both the unscaled and scaled tolerances. In general, E_{ellipse} and A_{ellipse} are much more similar when scaled. The comparison of the tolerances is concluded in the next section by analyzing the actual and scaled ΔA and ΔE values for the limit samples and three ellipsoid boundary points for the four color sets.

Numerical Comparison of ΔA and ΔE Values

The previous section showed that the ΔA and ΔE methods are quite similar when compared on the average color difference for a set of limit samples. A final comparison of the methods can be made by examining the actual color difference values for all the limit samples. The unscaled and scaled ΔA and ΔE values for the limit samples and three ellipsoid boundary points (at an end of each axis) for the four color sets are listed in Table IV. To make a direct comparison of the color values, the average and standard deviation of the scaled ΔA and ΔE values were computed for each color set. These are found to be within 0.05 color difference units indicating close agreement between the methods.

A scatter plot of the ΔA and ΔE color differences for each color set is given in Figure 8. The correlation between the sets of ΔA and ΔE values is no lower than 0.95 for each color. The high correlation and proximity to the 45° line confirm the similar behavior of the two methods for calculating color difference. Of course, the same correlation applies to the unscaled values, but with a different scaling factor for each color set.

The two methods can be compared through acceptability criteria as well as correlation on color difference values. After scaling, a value of ΔA or ΔE less than 1.0 means acceptance of the sample, while a value greater than one means rejection. For the total set of 49 color measure-

ments, only four samples are accepted by one method and rejected by the other. These instances are the olive green full standard sample, FS; the tan #1 thin yellow sample, TY; the tan #2 thin green sample, TG; and the dark blue full blue sample, FB. In each case, these are accepted under ΔE but rejected using ΔA . The remainder of the samples examined (45 instances) are either mutually rejected or accepted using ΔA and ΔE . The two methods agree on over 91% of the samples examined, providing further evidence of their basic similarity.

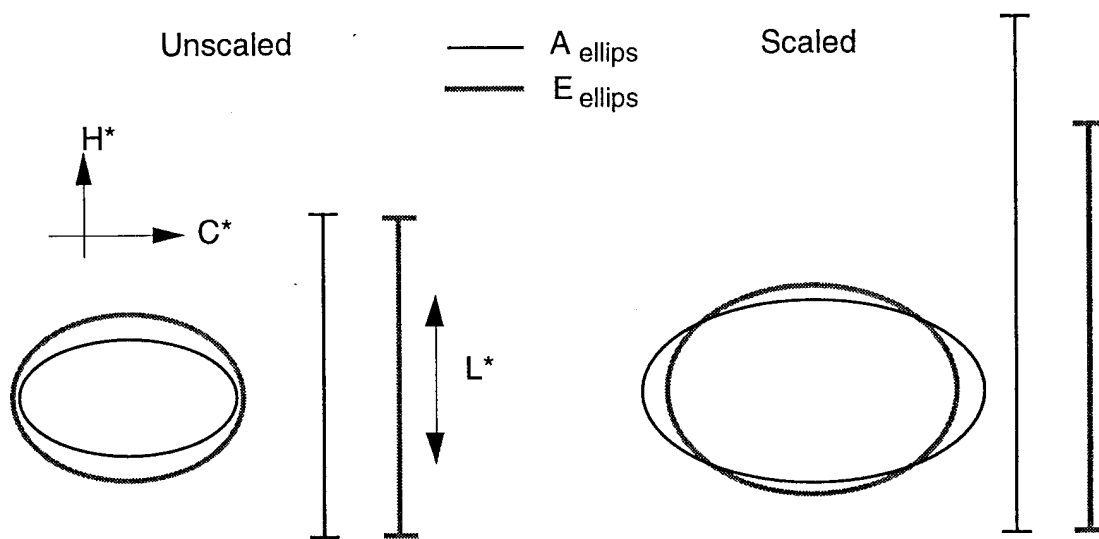


Figure 4. Relative ΔA and ΔE tolerances for olive green standard

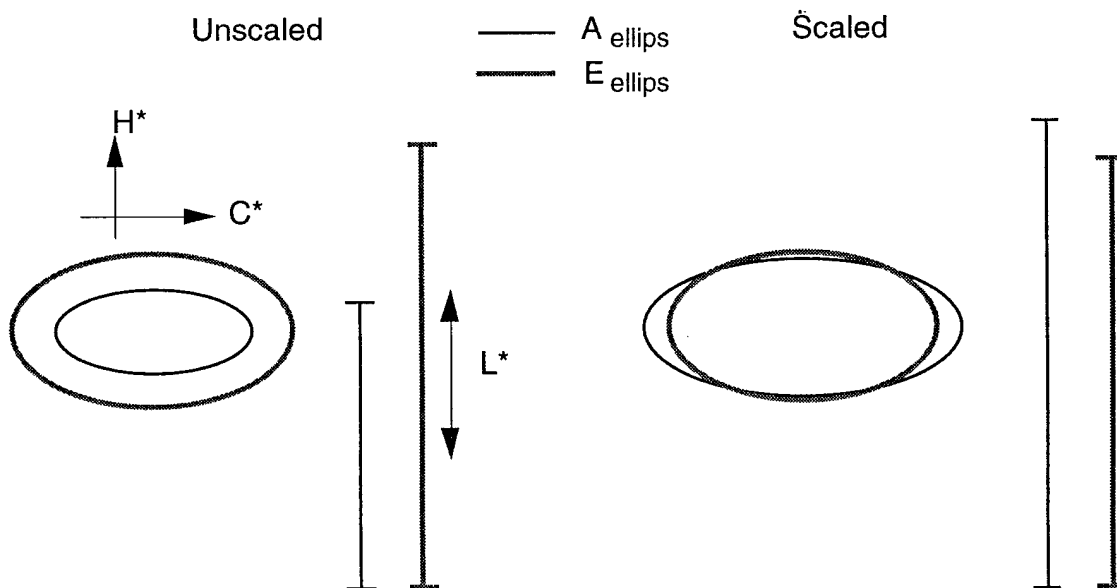


Figure 5. Relative ΔA and ΔE tolerances for tan (#1) standard

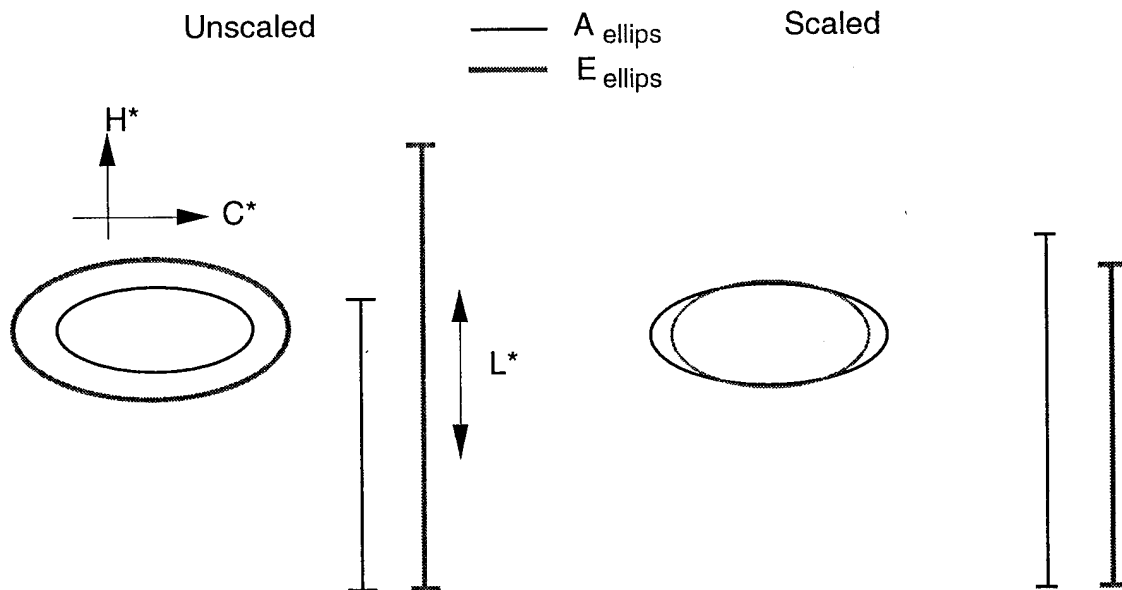


Figure 6. Relative ΔA and ΔE tolerances for tan (#2) standard

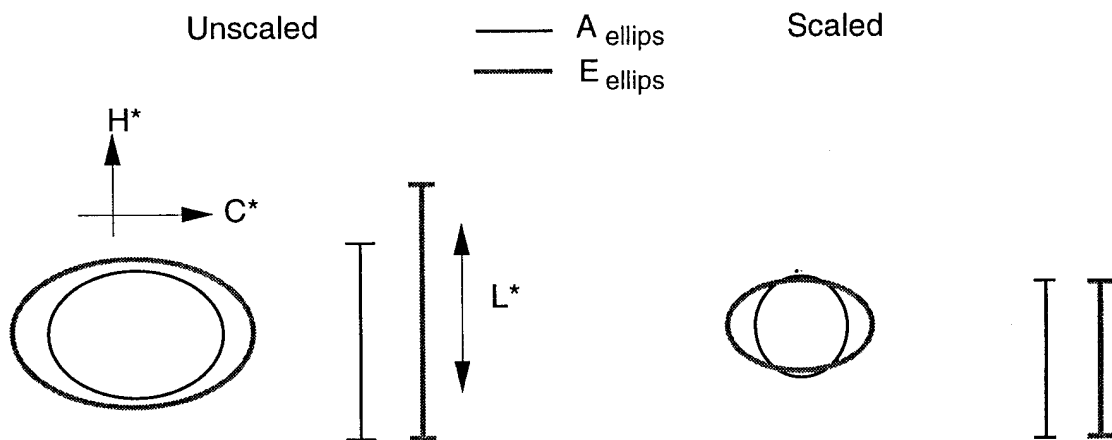


Figure 7. Relative ΔA and ΔE tolerances for dark blue standard

Table IV. Comparison of ΔA and ΔE Values

Sample	Unscaled ΔA	Unscaled ΔE	Scaled ΔA	Scaled ΔE	Sample	Unscaled ΔA	Unscaled ΔE	Scaled ΔA	Scaled ΔE
Olive Green					Tan, Set No. 1				
FY	2.287	1.668	1.429	1.313	FY	2.073	1.255	1.272	1.307
FS	1.777	1.254	1.111	0.988	FS	2.840	1.580	1.742	1.646
FG	1.388	1.172	0.867	0.923	FG	1.079	0.669	0.662	0.697
FB	1.441	1.090	0.901	0.858	FB	0.914	0.532	0.561	0.554
FR	1.336	0.984	0.835	0.775	FR	3.092	1.689	1.897	1.759
TG	1.301	1.141	0.813	0.898	TR	1.529	0.907	0.938	0.944
TY	1.214	0.917	0.759	0.722	TY	1.509	0.982	0.926	1.023
TB	2.382	1.882	1.489	1.482	TB	0.556	0.355	0.341	0.370
TS	1.738	1.339	1.086	1.054	TS	1.111	0.704	0.682	0.734
C*max	0.998	0.938	0.623	0.739	C*max	0.998	0.700	0.612	0.729
H*max	1.001	0.691	0.625	0.544	H*max	1.000	0.542	0.613	0.564
L*max	1.000	1.008	0.625	0.794	L*max	1.000	0.646	0.614	0.673
Avg.				0.930	Avg.				0.905
St. Dev.				0.295	St. Dev.				0.488
Tan, Set No. 2					Dark Blue				
FY	0.979	0.605	0.810	0.840	FG 1	2.020	1.551	2.525	2.585
FS	0.788	0.448	0.651	0.623	FS	0.485	0.381	0.606	0.635
FG	1.503	0.849	1.242	1.180	FG 2	0.943	0.735	1.179	1.224
FB	1.157	0.697	0.956	0.968	FB	0.757	0.628	0.946	1.046
FR	1.657	0.934	1.369	1.298	FR	0.858	0.687	1.073	1.145
TR	1.262	0.810	1.043	1.124	TR	0.170	0.137	0.212	0.228
TY	1.637	0.932	1.353	1.294	TB	0.668	0.528	0.835	0.881
TB	0.731	0.472	0.604	0.655	TS	0.505	0.384	0.631	0.640
TS	1.086	0.708	0.898	0.983	TG	0.471	0.360	0.589	0.600
TG	1.258	0.704	1.039	0.978	C*max	0.999	0.732	1.249	1.220
C*max	0.998	0.710	0.825	0.986	H*max	1.001	0.845	1.251	1.409
H*max	1.001	0.560	0.827	0.778	L*max	1.000	0.769	1.250	1.281
L*max	1.000	0.652	0.827	0.905					
Avg.				0.970	Avg.				0.893
St. Dev.				0.251	St. Dev.				0.348

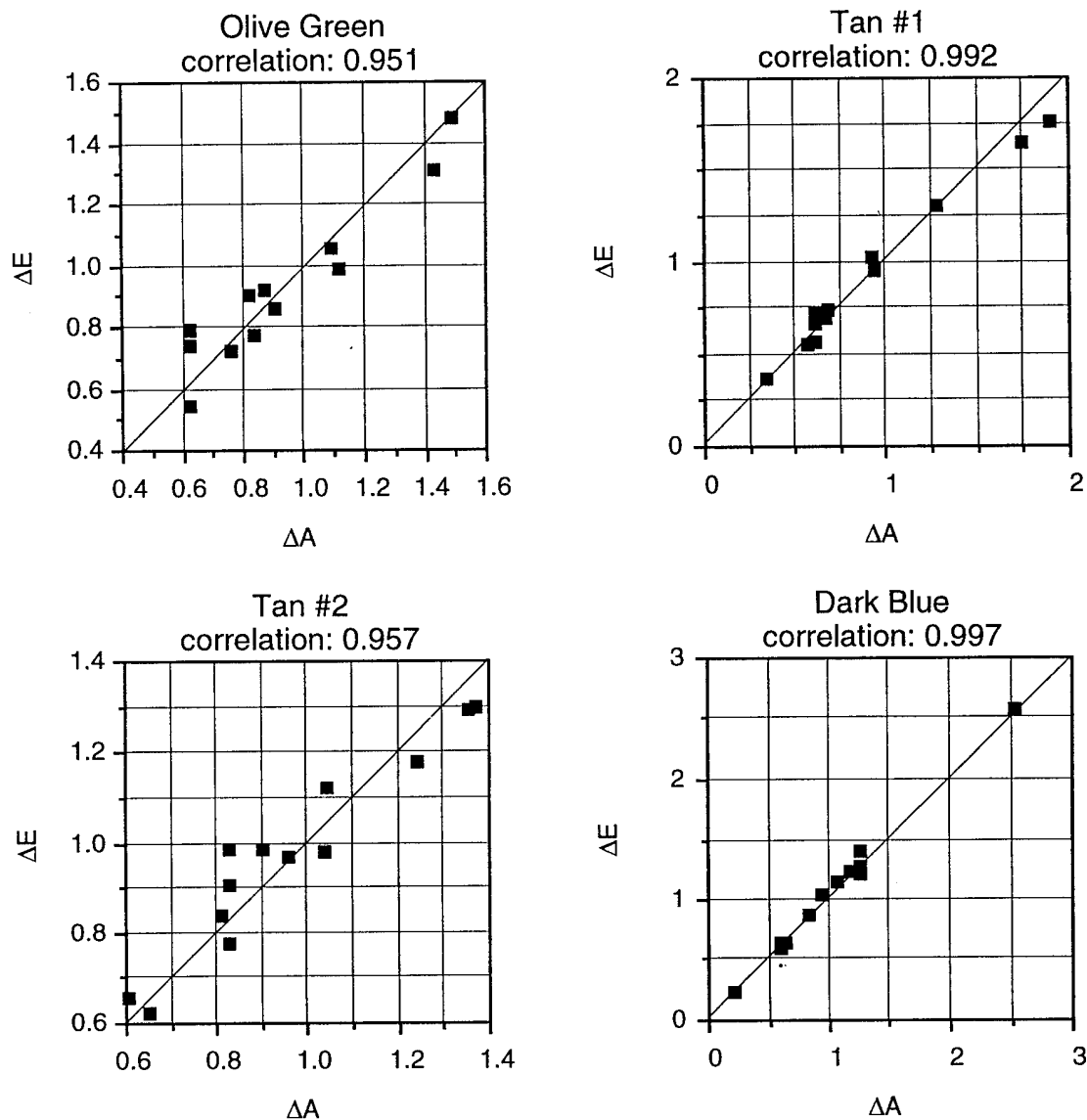


Figure 8. Scatter plots of scaled ΔA vs. ΔE color difference values

Summary

For a given standard, the ΔE color difference formula is essentially equivalent to the ΔA color difference formula when the lightness, chroma, and metric hue tolerances are set to the same values for both methods. The only difference lies in the approximations to ΔC and ΔH which the ΔA method uses. For practical use, these approximations introduce no significant difference in the color difference values.

The lightness, chroma, and hue tolerances employed in ΔA have been determined for only a few specific colors. In contrast, the CMC color difference method includes procedures for determining these tolerances for any color. For the few colors for which the ΔA tolerances are avail-

able, the ΔA tolerances are quite similar to those for ΔE when standardized. In addition, the actual color difference values for these color sets had correlation coefficients of 0.98 or higher. The acceptability results produced by ΔA and ΔE are also nearly identical. For four standards and 37 associated limit samples, the acceptability decision for the two methods differed on only four samples (one for each standard).

These similarities suggest that the replacement of the proprietary ΔA method by the industry standard ΔE method can proceed with little difficulty or change in acceptance criteria. Finally, note that there are two major advantages of ΔE over ΔA . First, the considerable experimental effort required to establish tolerances has been done for all of color space for ΔE but for only a few colors for ΔA . Second, software for ΔE is widely available, but not so for ΔA . In the next two sections we develop the ΔE acceptability critical values for two specific fabrics—four-color woodland camouflage and three-color desert camouflage.

WOODLAND GREEN CAMOUFLAGE DATA ANALYSIS

The previous analysis demonstrates that the ΔA and ΔE color difference formulae are based on the same underlying principles. Although the two formulae do not produce the same color difference values for any particular standard and sample, these values are highly correlated (90% level or higher). As a result, it is possible to translate critical values derived for ΔA to equivalent values for ΔE . For each standard, if the ΔA tolerances and critical values have been established and if there are sufficient samples to determine the correlation between the ΔA and ΔE color difference values, then the ΔE critical value can be obtained from the corresponding ΔA value by a simple multiplication. In particular, the critical values for each method are related by the same multiplier.

For ΔA , the critical value depends on the standard color of the samples being tested. However, for ΔE , the *same* critical value should be applicable to *every* standard. What has not been examined is whether different ΔA critical values for multiple standards translate to approximately the same ΔE critical value. This question is problematic because ΔA tolerances and critical values have been established for so few standards. Fortunately for our purposes, these values have been determined for the component colors of four-color woodland green camouflage.

The woodland green camouflage pattern contains four different colors: light green 354, dark green 355, dark brown 356, and black 357. Extensive colorimetric data was gathered in an industry trial conducted by Natick and DPSC [4]. The trial was performed by Barbara Fitzgerald in 1992 on 15 lots of woodland green camouflage printed nycotex twill. Although DPSC procures woodland camouflage fabric from several different producers, Delta Mills was the sole contributor of data to the 15 Lot Study. Since the trial indicated good agreement between visual and instrumental ΔA pass/fail judgments, we could determine ΔE acceptability criteria on the pre-established ΔA tolerance values.

Colorimetric Data Analysis

There were 779 samples in the Natick study. The colorimetric data for these samples were obtained from Natick and carefully examined. The total number of measurements available for each color varied because of some missing data (sometimes a measurement for a particular color could not be obtained from a certain sample). In addition, at least eight of the study lots have measurements made relative to multiple standards, not all of which had colorimetric data available.

Since each lot and separate portions of some lots were measured and evaluated relative to different standards, each sample and its associated standard were identified. This was done to insure consistency in establishing correlations between ΔA and ΔE color differences. (Recall that ΔE color differences are computed using tolerances determined by the standard.) There were 766

samples of light green 354 of which only 498 could be identified with a known standard value. For the dark green 355, 598 of the 791 samples could be matched with a standard. There were 664 of the 766 and 555 of the 765 samples that could be identified for the dark brown 356 and black 357, respectively. Due to the results of the ΔA - ΔE comparison and the large number of samples available, a high correlation between the ΔA and ΔE values was expected and found. Figures 9–12 illustrate the high ΔA - ΔE correlations for those samples that could be associated with a standard.

Ideally, ΔE critical values should be obtained directly from the pass/fail decisions made on the sample data. However, for the Natick data, visual pass/fail assessments indicated only twenty-six light green failures and one dark green failure. These represent insufficient data to determine critical values directly. Fortunately, the high correlations between ΔA and ΔE color differences observed in the analysis of the four data sets indicate that the calculated regression lines could be used to predict the ΔE critical values for the four colors from the existing ΔA critical values.

Table V lists the existing ΔA values and the predicted ΔE values. For the woodland camouflage, the ΔA critical values for acceptance are 1.00 (black), 1.30 (brown), 1.60 (light green), and 1.60 (dark green). When converted to ΔE , these values are 2.13, 1.68, 1.69, and 1.72 respectively. With the exception of the black, the uniformity of these critical values is consistent with the current industry practice of using a single ΔE critical value for all colors. If this exception can be resolved, these results suggest that the changeover to ΔE_{CMC} should be relatively straight forward for the woodland camouflage and that the CMC color difference formula could be used to determine appropriate critical values for other colors and fabrics.

Table V. Predicted ΔE Critical Values for Four-color Woodland Camouflage

Color	Critical Values	
	ΔA	ΔE
Light Green 354	1.6	1.69
Dark Green 355	1.6	1.72
Dark Brown 356	1.3	1.68
Black 357	1.0	2.13

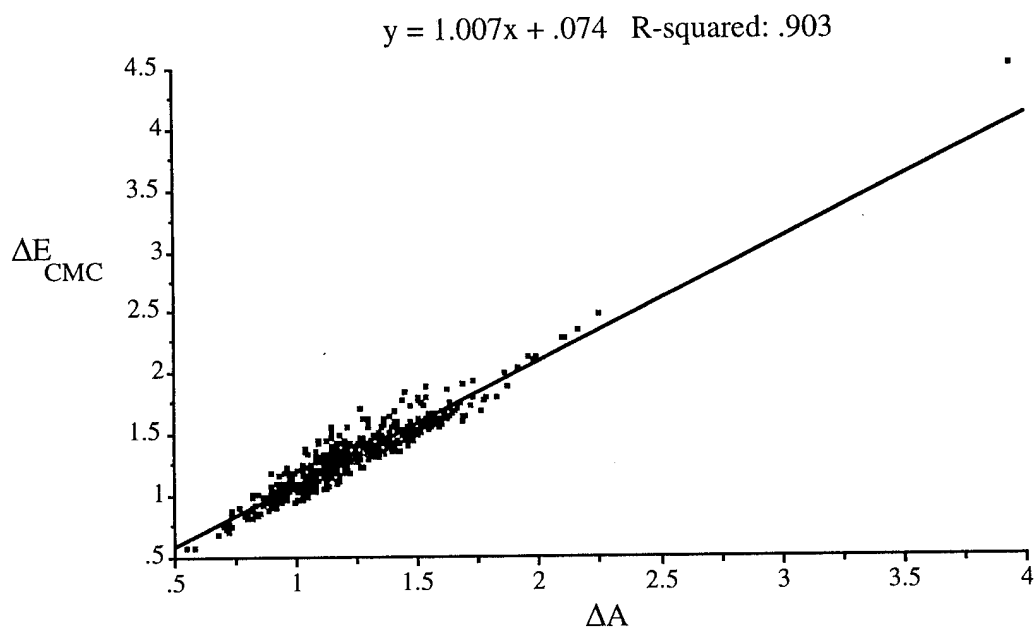


Figure 9. Scatter plot of ΔA vs. ΔE for light green 354

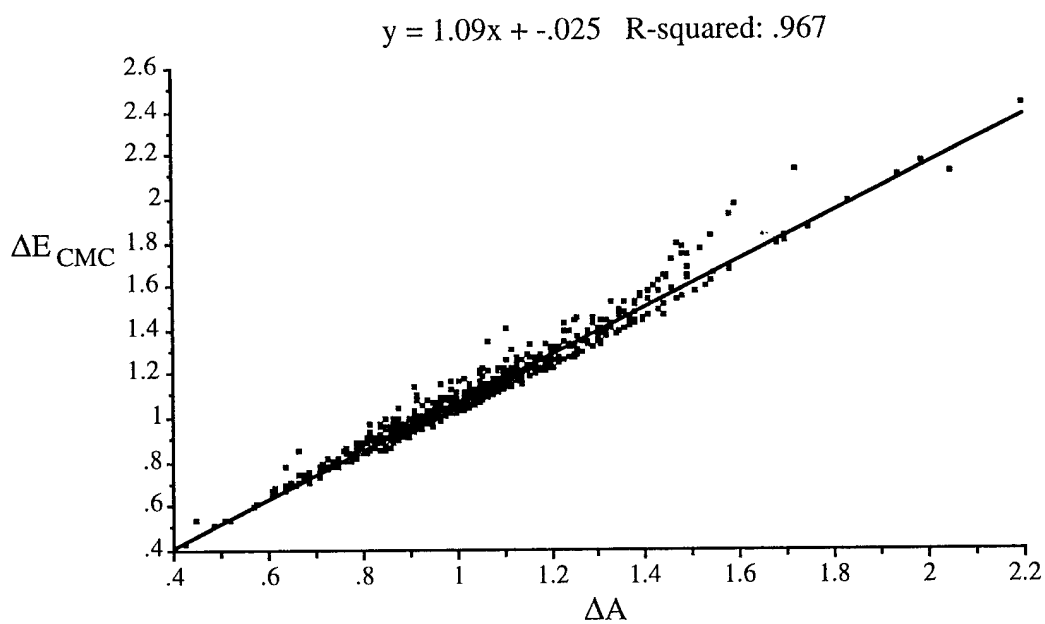


Figure 10. Scatter plot of ΔA vs. ΔE for dark green 355

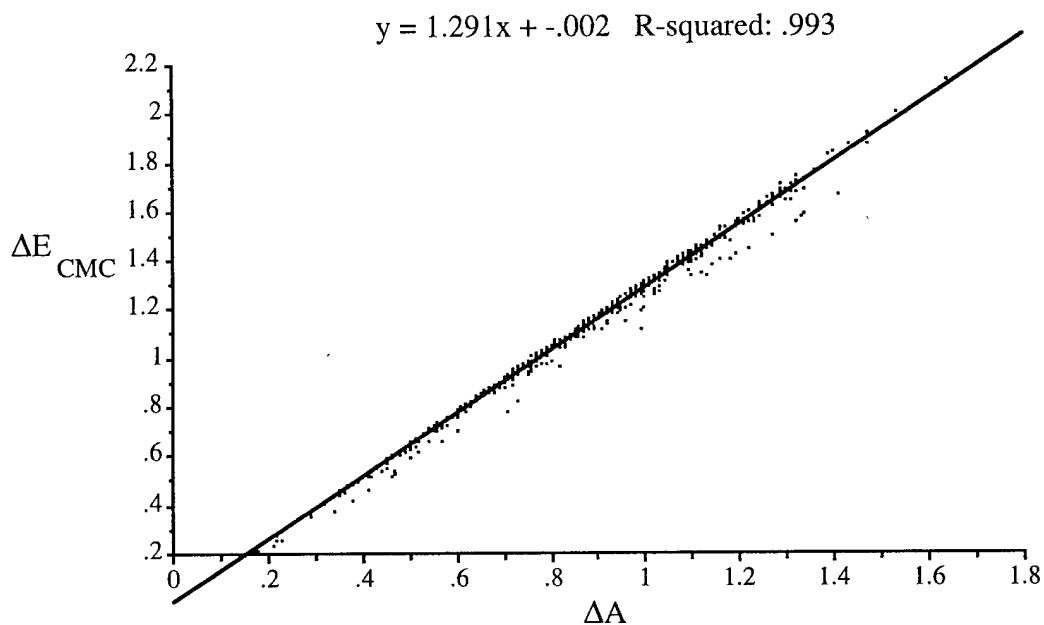


Figure 11. Scatter plot of ΔA versus ΔE for dark brown 356.

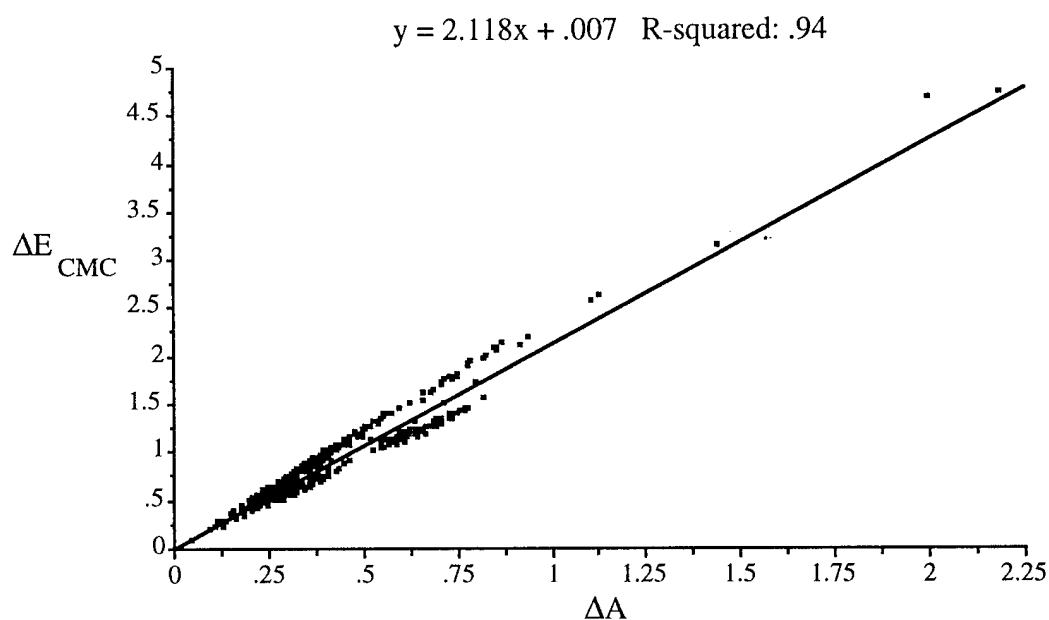


Figure 12. Scatter plot of ΔA versus ΔE for black 357.

Setting Critical Values for Acceptance

The use of the ΔE color difference formula is predicated on the assumption that a color difference of 1.0 can be interpreted similarly for all shades. This suggests the existence of a single critical value for all colors and fabrics. Representatives from Natick and Clemson met in August

1994 to discuss setting ΔE critical values for the 4-color woodland camouflage. The predicted ΔE critical values for the light green, dark green and dark brown were not significantly different from a 1.7 critical value. Because of the smaller number of samples considered in setting the ΔA critical value for black, all parties agreed that a critical value of 1.7 would be appropriate for black as well. This agreement was based on the confidence of Natick personnel in the ΔA critical values for the woodland green camouflage, the high correlation between ΔA and ΔE observed in all data analyzed at Clemson, and the similarity of the derived ΔE critical values for those shades represented by extensive data. In the next section, we will test the application of this single critical value of 1.7 on a different pattern and shades—three-color desert camouflage.

DESERT CAMOUFLAGE DATA ANALYSIS

The desert camouflage pattern contains three different shades: light tan 492, light khaki 494, and light brown 493. The type of analysis described in the previous section is not applicable to desert camouflage because neither the ΔA tolerances nor critical values for acceptance have been determined for the shades of this pattern. The alternative considered here is examination of physical limit samples. Typically, the physical limit samples are swatches with shades denoted "thin yellow," "full yellow," "thin blue," "full blue," etc., which serve to define the limits of acceptable shade variation. If these limit samples have this property, they should be near the boundary of the acceptability ellipsoid in color space and hence could be used to estimate the semi-axis lengths of the ellipsoid. Based on our analysis of woodland green camouflage, we would expect that this ellipsoid would be associated with a ΔE critical value of 1.7.

Colorimetric Data Analysis

We received 29 samples of tan 492, 28 samples of khaki 494, and 15 samples of brown 493 in twill, sateen, and oxford, as well as the standards for each. These samples were measured according to government specifications using an X-Rite SP78 Spherical Spectrophotometer. All ΔE calculations were performed using CMC (2:1). Tables VI–VIII contain a tabulation of the colorimetric data and ΔE color difference values for the three colors. The samples are listed by increasing ΔE per fabric. The limit samples exhibit a wide range of color variation, although generally falling between 1.0 and 2.0 ΔE units. All the light khaki samples fall within the 1.7 ΔE boundary; most of the light brown samples lie above this boundary; the light tan values are intermediate.

The interpretation of these data is somewhat problematic. If a 1.7 ΔE critical value were strictly applicable, then 46% of the 29 light tan limit samples, 0% of the 28 light khaki samples, and 67% of the 15 light brown samples would be judged unacceptable. These percentages might, at first, seem too large. Recall, however, that the developments of both ΔA and ΔE were not based on strict pass/fail judgments. For ΔE in particular, a critical value of 1.0 is associated with an ambivalent judgment as to acceptability. In this light, we might expect a failure rate of roughly 50% if the physical limit samples were all close to the boundary of the acceptability ellipsoid. Unfortunately, this is not the case. All the light khaki samples lie within 1.7 ΔE boundary that brings into question whether a limit has really been established. In turn, both the light tan and light brown samples exhibit such extreme variation in shade that it is difficult to associate any boundary surface with the values.

For each shade and fabric, the colorimetric data are plotted with a 1.7 ΔE acceptability ellipsoid in Figures 13–21. Each figure shows the standard and those samples which pass or fail. These figures emphasize the variation in the colorimetric data for the limit samples.

Table VI. Standard and Limit Sample Colorimetric Data for Light Tan 492.

SAMPLE	L*	a*	b*	C*	h°	ΔE
Nyco Twill						
Standard #3477	65.00	6.38	13.13	14.60	64.08	0.00
3	65.20	6.71	13.54	15.11	63.64	0.42
4	62.24	6.60	13.22	14.78	63.47	1.15
8	63.36	7.15	13.55	15.32	62.18	1.16
1	67.81	6.23	12.41	13.89	63.34	1.27
11	62.21	5.77	12.27	13.56	64.81	1.37
10	63.08	6.16	11.62	13.15	62.07	1.50
5	62.42	6.96	12.42	14.24	60.73	1.73
9	63.23	7.73	13.78	15.80	60.71	1.82
2	66.58	7.87	13.94	16.01	60.55	1.93
6	62.67	7.54	12.78	14.84	59.46	2.15
7	62.48	7.68	13.09	15.18	59.60	2.18
Nyco Sateen						
Standard #3479	65.24	6.79	12.72	14.42	61.91	0.00
30	63.42	6.98	12.04	13.92	59.90	1.17
25	68.02	6.90	12.08	13.91	60.27	1.36
27	64.03	7.03	11.52	13.50	58.61	1.58
28	61.06	6.63	12.41	14.07	61.89	1.70
26	63.75	7.03	11.40	13.39	58.34	1.73
24	67.34	5.68	12.37	13.61	65.34	1.74
31	63.62	7.59	11.90	14.11	57.47	1.98
32	62.89	5.59	12.91	14.07	66.59	2.19
29	61.34	8.05	12.53	14.89	57.28	2.56
Oxford						
Standard #3478	67.58	6.60	12.45	14.09	62.07	0.00
51	68.57	5.75	11.63	12.97	63.69	1.10
54	69.17	5.94	12.24	13.61	64.11	1.10
52	68.28	5.69	11.64	12.96	63.95	1.14
55	70.23	6.14	11.59	13.12	62.09	1.26
56	66.05	7.71	14.03	16.01	61.21	1.55
59	68.46	5.80	12.84	14.09	65.69	1.55
58	65.97	7.73	14.61	16.53	62.12	1.86
57	65.97	7.83	14.59	16.56	61.78	1.88
53	69.67	5.17	11.72	12.81	66.20	2.05

Table VII. Standard and Limit Sample Colorimetric Data for Light Khaki 494

SAMPLE	L*	a*	b*	C*	h°	ΔE
Nyco Twill						
Standard #3477	59.24	2.15	16.68	16.82	82.66	0.00
16	58.59	2.09	17.23	17.36	83.08	0.47
13	60.06	2.93	16.63	16.89	80.01	0.99
14	61.68	1.70	16.40	16.49	84.08	1.16
17	56.36	1.73	16.68	16.77	84.08	1.31
18	56.67	2.80	17.29	17.52	80.80	1.35
12	60.71	1.16	15.56	15.60	85.74	1.45
15	61.38	1.86	14.79	14.91	82.83	1.55
Nyco Sateen						
Standard #3479	61.06	2.65	16.39	16.60	80.82	0.00
35	61.60	3.34	17.32	17.64	79.09	0.96
37	63.05	2.08	15.60	15.74	82.41	1.15
44	58.44	3.06	16.77	17.05	79.66	1.20
41	59.40	3.37	17.62	17.94	79.17	1.28
36	63.21	1.97	15.50	15.62	82.76	1.29
38	58.97	3.37	17.29	17.62	78.97	1.29
33	61.82	3.13	14.91	15.23	78.14	1.32
43	58.20	2.73	17.27	17.48	81.02	1.33
42	59.61	3.44	17.99	18.32	79.17	1.42
39	59.61	3.78	16.72	17.14	77.26	1.46
40	56.99	2.59	16.47	16.67	81.06	1.69
34	62.71	3.14	14.49	14.83	77.77	1.70
Oxford						
Standard #3478	64.00	3.13	16.13	16.43	79.02	0.00
60	64.03	2.76	15.49	15.73	79.90	0.56
64	65.54	3.11	15.87	16.17	78.91	0.65
61	64.99	2.72	15.19	15.43	79.85	0.83
66	62.05	3.61	16.56	16.95	77.70	0.99
63	66.26	2.37	15.84	16.02	81.49	1.30
68	61.34	3.13	17.31	17.59	79.75	1.36
62	65.70	2.56	14.34	14.57	79.88	1.45
65	63.17	2.58	17.78	17.97	81.74	1.49
67	61.23	3.09	17.88	18.15	80.20	1.66

Table VIII. Standard and Limit Sample Colorimetric Data for Light Brown 493

SAMPLE	L*	a*	b*	C*	h°	ΔE
Nyco Twill						
Standard #3477	41.14	12.17	16.82	20.76	54.11	0.00
23	41.82	12.18	17.34	21.19	54.91	0.64
22	42.54	11.18	16.38	19.83	55.68	1.27
19	37.41	11.36	16.20	19.79	54.96	2.05
21	42.67	15.19	18.31	23.79	50.32	3.08
20	42.32	15.16	18.06	23.58	49.99	3.13
Nyco Sateen						
Standard #3479	38.49	12.43	15.90	20.18	51.98	0.00
47	36.46	11.52	14.43	18.46	51.40	1.53
46	36.58	11.47	14.30	18.33	51.27	1.56
50	35.54	11.56	14.56	18.59	51.55	1.86
45	41.71	11.04	14.68	18.37	53.06	2.11
48	34.79	11.49	14.08	18.17	50.78	2.40
49	35.44	10.88	13.29	17.18	50.69	2.52
Oxford						
Standard #3478	41.43	10.75	16.04	19.31	56.17	0.00
72	41.12	9.94	16.10	18.92	58.31	1.22
69	44.34	10.67	16.86	19.95	57.67	1.76
70	43.91	11.09	17.75	20.93	58.00	1.93
71	44.83	10.81	17.02	20.16	57.58	1.98

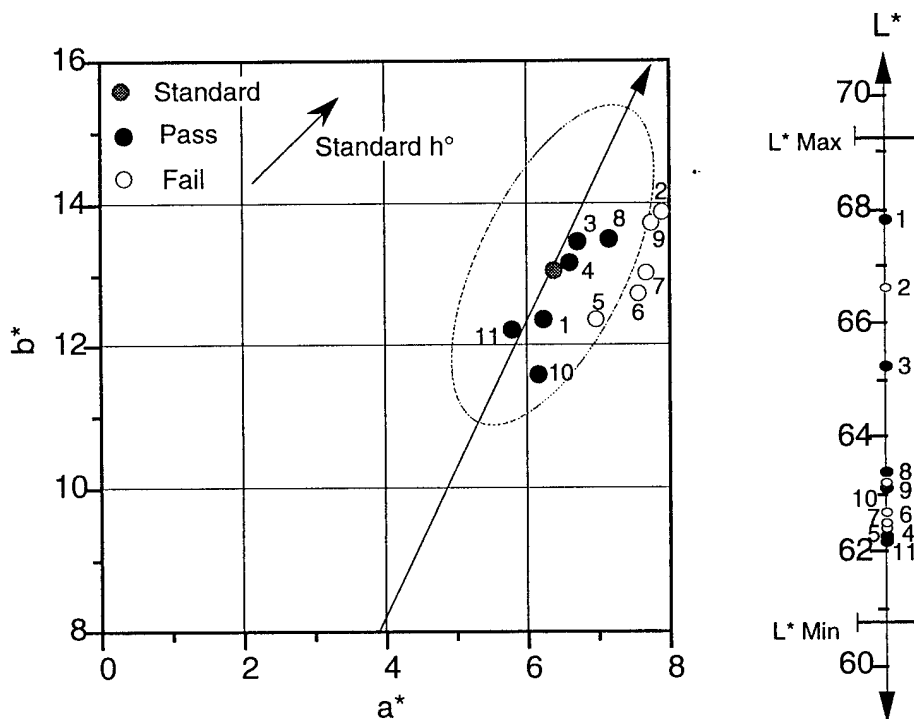


Figure 13. Scatter plot of limit samples for Light Tan 492: Nyco Twill

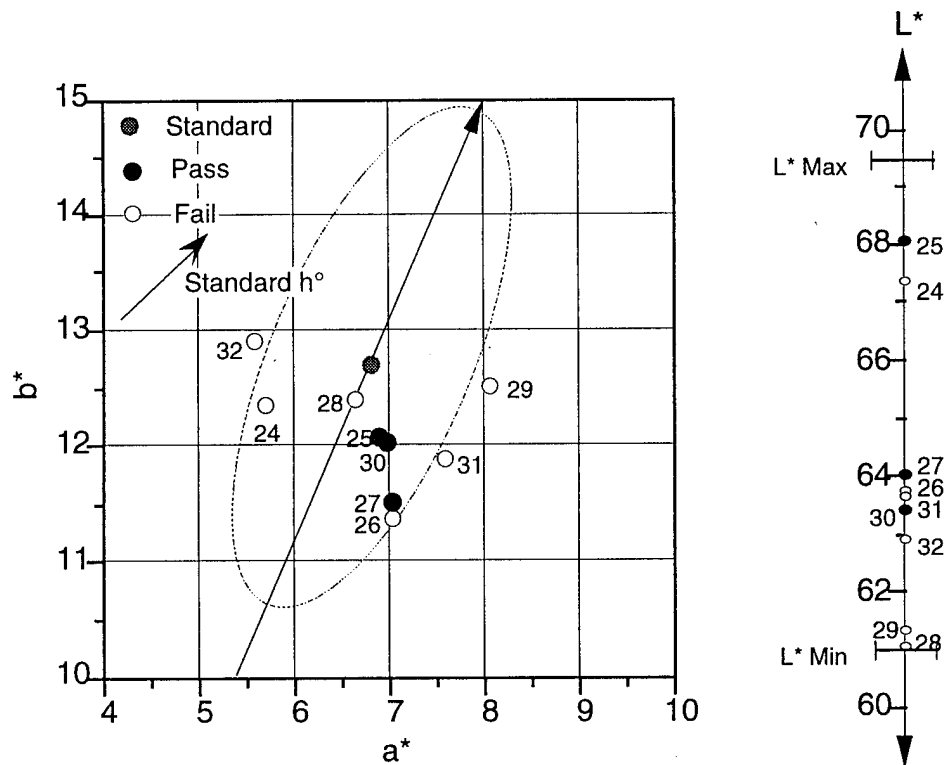


Figure 14. Scatter plot of limit samples for Light Tan 492: Nyco Sateen

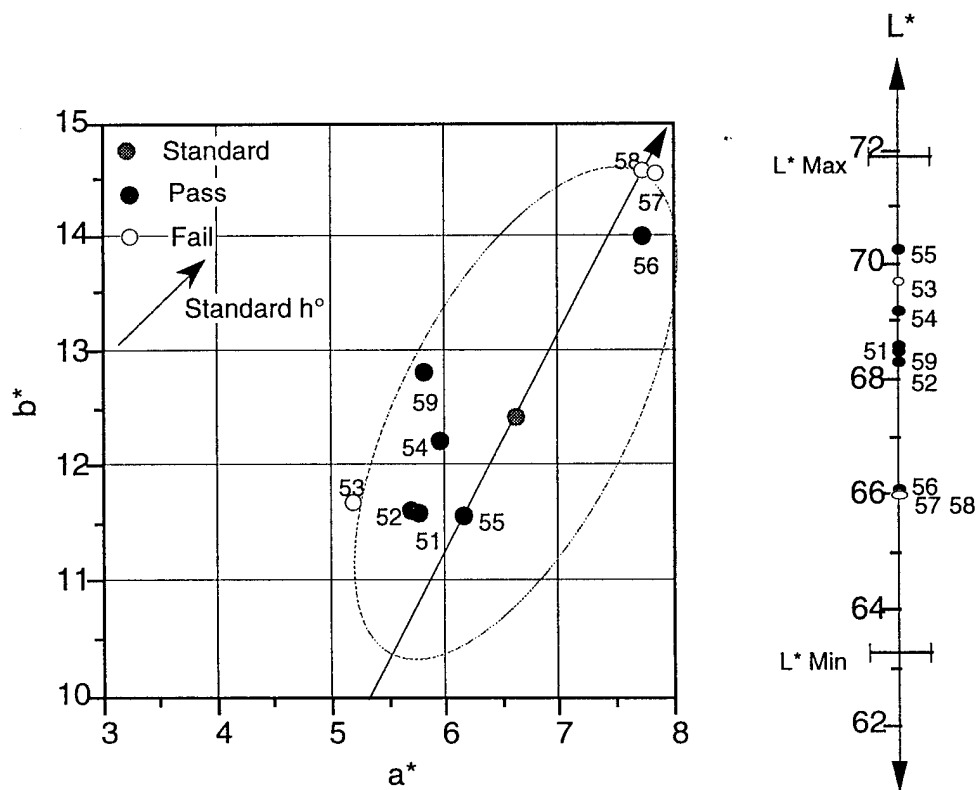


Figure 15. Scatter plot of limit samples for Light Tan 492: Oxford

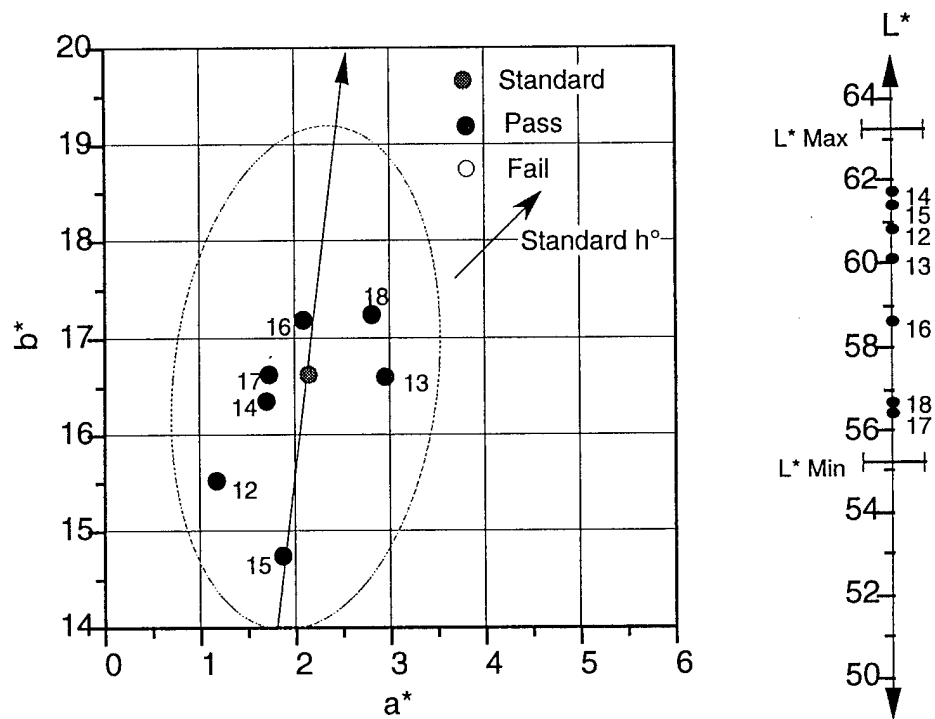


Figure 16. Scatter plot of limit samples for Light Khaki 494: Nyco Twill

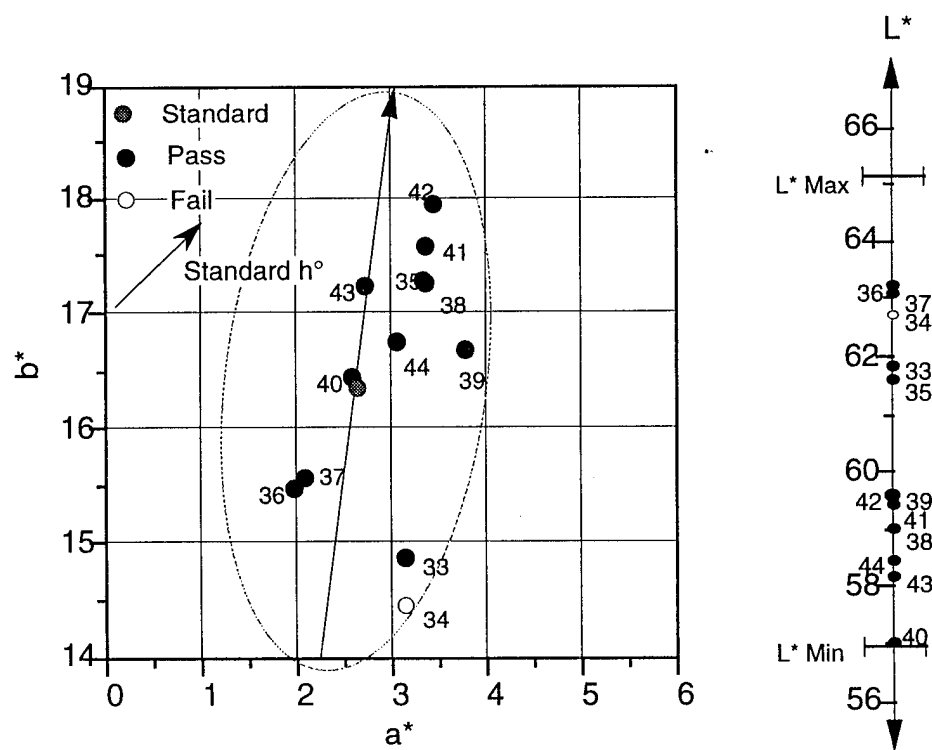


Figure 17. Scatter plot of limit samples for Light Khaki 494: Nyco Sateen

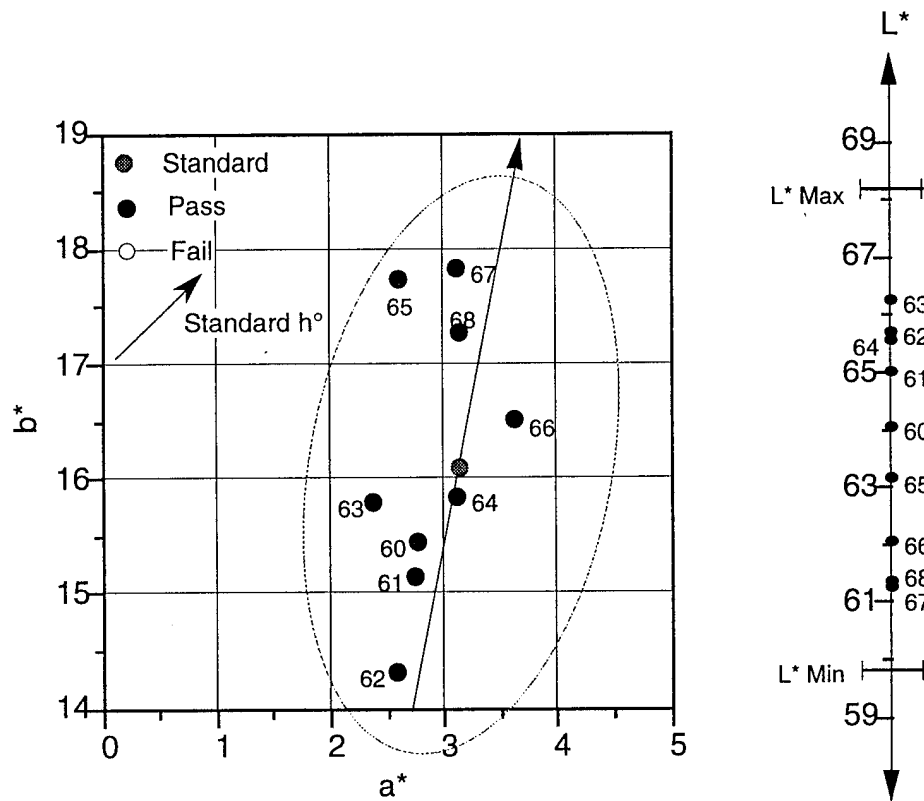


Figure 18. Scatter plot of limit samples for Light Khaki 494: Oxford

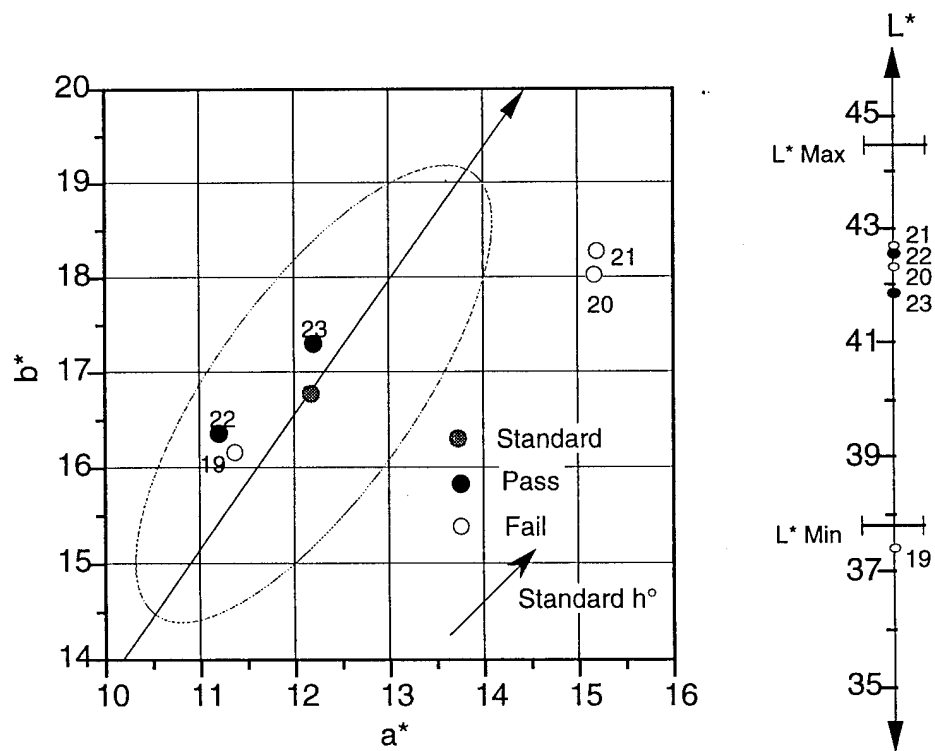


Figure 19. Scatter plot of limit samples for Light Brown 493: Nyco Twill

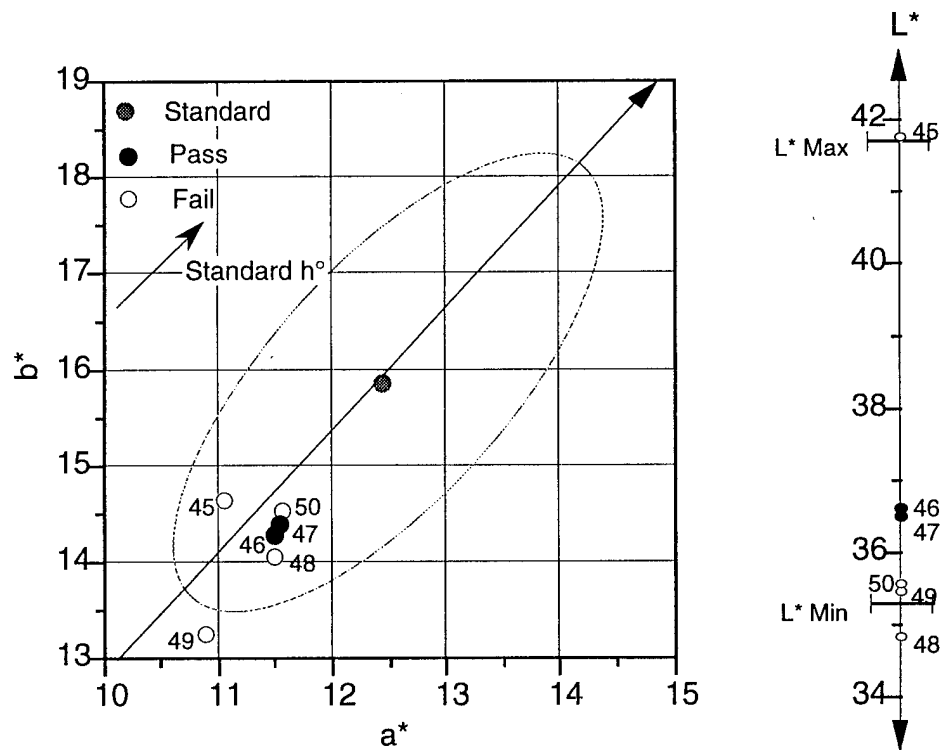


Figure 20. Scatter plot of limit samples for Light Brown 493: Nyco Sateen

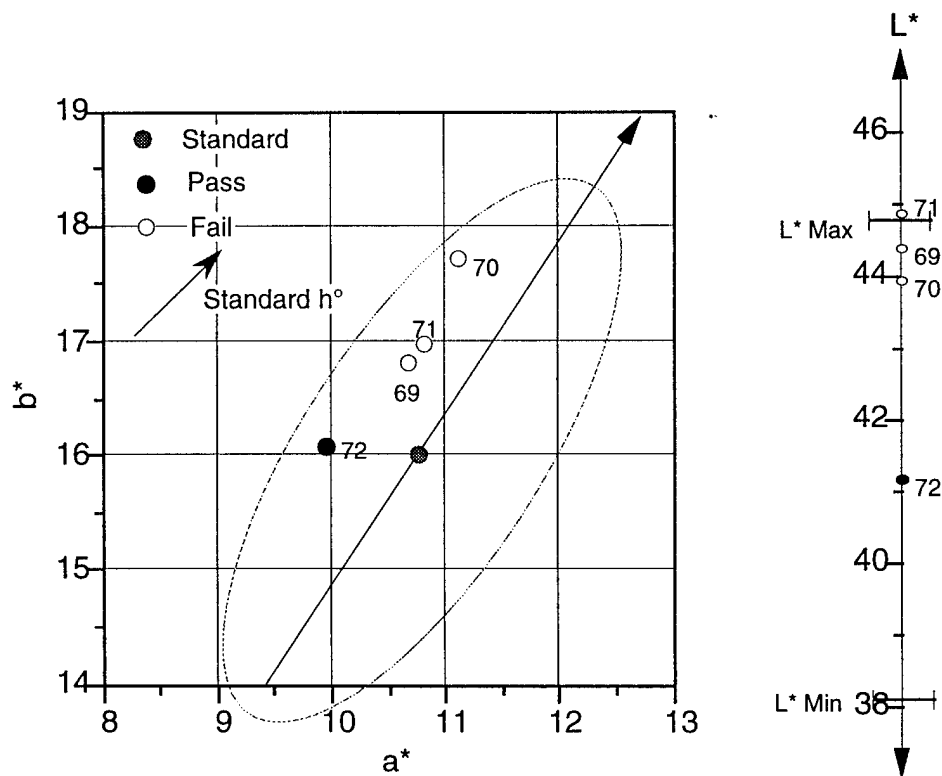


Figure 21. Scatter plot of limit samples for Light Brown 493: Oxford.

In trying to interpret these values, it should be noted that these physical limit samples are similar in their range to those for woodland green camouflage. The woodland green camouflage physical limit samples were examined early in this study to locate the acceptability ellipsoid boundaries for those shades. As the values in Table IX indicate, the variation in color difference from the standards was substantial for every shade and fabric examined. In addition, using the 1.7 ΔE critical value derived from other data, a majority of these limit samples would be judged unacceptable. Hence, the shade variations for the desert camouflage physical limit samples are similar to those for the woodland green camouflage.

Table IX. Variation in Colorimetric Data for Woodland Green Camouflage

Fabric	Samples	Min ΔE	Max ΔE	Failures
Dark Green Cotton Ripstop	4	0.60	4.60	75%
Dark Green Nyco Twill	16	0.63	5.09	56%
Light Green Cotton Ripstop	16	1.11	5.75	75%
Light Green Nyco Twill	12	1.18	3.31	83%
Brown Cotton Ripstop	10	1.44	4.64	70%
Brown Nyco Twill	17	0.74	4.71	76%
Black Cotton Ripstop	1	4.73	4.73	100%
Black Nyco Twill	3	2.14	2.31	100%

It is inherent to the ΔE_{CMC} (and the proprietary ΔA) color difference formula that samples having the same calculated color difference from the standard will be visually assessed in a similar way. This will be true regardless of whether the actual color difference is primarily in lightness, chroma, hue, or some combination of these. For both the woodland green and the desert camouflage, the physical limit samples were problematic. These samples exhibit a wide range of color differences that are inconsistent with both the ΔE_{CMC} and the ΔA color difference formulae if used to define an acceptance region. Given the extensive satisfactory use of ΔE_{CMC} within the apparel and textile industry, the physical limit samples for desert camouflage present no compelling evidence to reject the use of a 1.7 ΔE critical value for that pattern as well.

In this context, our choice of 1.7 for a critical value for the desert camouflage was based on Natick's extensive tests on the woodland green camouflage in addition to the limit samples for the woodland green and desert camouflage. The credibility of this choice is enhanced by the almost startling consistency of the ΔA critical values established by Natick for woodland green camouflage when converted to ΔE_{CMC} . Even here, the physical limit samples were not consistent in ΔE_{CMC} .

Recommendations

Given the lack of an extensive field trial using ΔA for acceptability testing for desert camouflage, we were forced to rely on physical limit samples to estimate a ΔE critical value. However, the extreme color variation within these samples prevented our obtaining any firm estimate. Noting the similar variation in the woodland green camouflage limit samples and the considerable experience in using ΔE_{CMC} in the industry, we recommend using the same 1.7 ΔE critical value as was obtained for the woodland green camouflage. Additional testing should be performed by Natick and DPSC to confirm this recommendation.

Addendum

We were able to conduct a small scale trial to test the 1.7 ΔE_{CMC} critical value. Natick supplied 84 samples of desert camouflage in nyco twill that was shipped during the Desert Storm operation. These samples were measured according to government specifications at Clemson Apparel Research. Summaries of the data gathered for the three colors in the desert camouflage samples are in Table X. No samples failed at the 1.70 critical value. It is our understanding that the rolls associated with these samples were all visually accepted and cut; thus, our recommendation of a 1.7 critical value stands.

Table X. Summary Colorimetric Data for Desert Camouflage Samples

Shade	Samples	Min ΔE	Max ΔE	Mean ΔE	St. Dev. ΔE
Light Khaki	84	0.15	1.70	0.84	0.380
Brown	84	0.20	1.58	0.67	0.293
Light Tan	84	0.15	1.12	0.60	0.204

CONCLUSIONS AND RECOMMENDATIONS

The ΔA and ΔE_{CMC} color difference formulae are based on the same underlying concept—equally perceptible color differences from a standard are described by the surface of an ellipsoid oriented by lightness, chroma, and hue. Although the two formulae do not produce the same color difference values for any particular standard and sample, these values are highly correlated (90% level or higher). As a result, it is possible to translate pass/fail values derived for ΔA to equivalent values for ΔE_{CMC} . ΔE_{CMC} is preferable to ΔA because of its wider acceptance and availability within the industry. In addition, determination of color tolerances for ΔA requires extensive data collection and analysis for every new color while ΔE_{CMC} embodies procedures for automatically determining the relevant color tolerances for every color. A fundamental tenet of the CMC color difference formula is a color difference of $\Delta E_{CMC}=1.0$ will be perceived identically for every color.

For the woodland camouflage, the ΔA critical values for acceptance are 1.00 (black), 1.30 (brown), 1.60 (light green), and 1.60 (dark green). When converted to ΔE_{CMC} , these values are 2.13, 1.68, 1.69, and 1.72 respectively. With the exception of the black, the uniformity of these critical values is consistent with the current industry practice of using a single ΔE_{CMC} critical value for all colors. Because there is some question as to the reliability of the critical value for black, a critical value of 1.7 is recommended for all colors in the woodland camouflage pattern.

Since there are no existing ΔA critical values for the three colors in the desert camouflage, physical limit samples were examined to determine appropriate critical values. These limit samples exhibited such extreme variation in color difference that no useful estimate of a critical value could be made directly. However, the same variation was seen for the woodland green camouflage limit samples. In a limited trial, the 1.7 critical value was found to be consistent with 84 samples of desert camouflage that had been accepted by the government.

We recommend a more extensive industry trial to test the use of a ΔE critical value of 1.7 for the desert camouflage. If there is high correlation between instrumental and visual color acceptability, then the critical value 1.7 should be considered for all colors in all fabrics. Statistical sampling procedures should be devised which will insure adequate testing for compliance with government specifications while easing the burden of measuring all goods submitted to the government.

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